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CONCEPTUAL DESIGN OF A CALORIMETER FOR GAMMA HEATING MEASUREMENTS IN THE PLUM BROOK REACTOR

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1.0 Summary

A conceptual design of a calorimeter is presented. The system equations are derived and solved. An out-of-pile experiment is proposed to determine the wall heat transfer coefficient and the turbulence factor α, which relates the bulk temperature to the centerline temperature. The calorimeter will be capable of operating continuously over a complete reactor cycle at full reactor power.

2.0 Introduction

The purpose of this paper is to show the analytical basis and conceptual design of a gamma heating calorimeter which provides a continuous indication of the gamma heating throughout a reactor cycle at full power.

In what follows, the concept is discussed first. Then the equations governing the system are derived and solved. Numerical methods of solving the gamma heating equations are discussed. Also the number of thermocouples required for the temperature profile is discussed. Finally a practical design which meets engineering constraints is proposed.

3.0 Symbols

A	cross sectional area of flow tube, ft^2
A_H	flow area, ft^2
C_1, C_2, C_3	defined on p. 7
C_p	specific heat capacity of water, Btu/(lb)(^oF)
h	heat transfer coefficient, Btu/(hr)(ft^2)(^oF)
I_n	defined on p. 10
K	thermal conductivity of flow tube, Btu/(hr)(ft)(^oF)
P	inside perimeter of flow tube, ft
Pr	Prandtl number, dimensionless

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dq_w differential amount of heat transfered from flow tube to fluid stream, Btu/hr

dq_Γ differential amount of heat generated in fluid stream, Btu/hr

dq_T total incremental heat gained ($dq_w + dq_\Gamma$), Btu/hr

$\overline{Q}$ average heat generation rate per unit volume, Btu/(hr)(ft^3)

$Q(x)$ heat generation rate per unit volume at position x, Btu/(hr)(ft^3)

Re Reynolds number, dimensionless

$\overline{T}_B$ average bulk water temperature, ^oF

$\overline{T}_B(x)$ bulk water temperature at position x, ^oF

T_c centerline temperature of flow stream, ^oF

$\overline{T}$ average surface temperature of flow tube, ^oF

$T_w(x)$ surface temperature at position x, ^oF

T_T thermocouple temperature, ^oF

w mass flow rate, lb/hr

x position in channel, ft

α turbulence factor, dimensionless

β,γ defined on p. 8

$\Gamma(x)$ mass heat generation rate at position x, watts/gm

τ dummy variable

$\Delta\theta$ time

ρ_H water density, lb/ft^3

ρ_M density of flow tube, lb/ft^3

φ defined on p. 8

4.0 Concept

A sketch of the calorimeter is shown in figure 1. The idea is to insert a vertical flow tube into a Plum Brook Reactor beryllium L-piece. A known mass flow of water moves down through the tube, and the temperatures of the water and the wall are sensed as the water traverses the flow tube.

When all the heat being generated in the tube is transferred locally to the water, and when the flow is known accurately, it is possible to construct the gamma heating profile in the channel from the measured temperature profiles.

Water is supplied to the flow tube at a known flow rate and temperature. The water flows down through a tube to the instrumented section of the flow tube which is located in the core. The flow is adjusted and measured by a calibrated flow meter located outside the reactor tank. Water exhausting from the flow tube mixes with the primary water exiting from the reactor core.

Two concepts are examined. One is a bulk rise calorimeter and the other a film drop calorimeter.

The bulk rise calorimeter works on the principle that the bulk temperature rise of a known water flow rate is directly proportional to the total heat energy deposited and inversely proportional to the mass flow rate.

The film drop calorimeter works on the principle that the local film drop is directly proportional to the local heat energy deposited and inversely proportional to the local heat transfer coefficient and surface area.

The proposed calorimeter uses both concepts. Thermocouples in the water and on the wall allow the determination of the gamma heat by both methods.

The calorimeter is designed to operate at high powers in the PBR. In addition, the calorimeter can operate continuously over a complete reactor cycle, and thus give a continuous indication of what effects rod bank height and fuel burnup have on the gamma heating.

5.0 Derivation of Equations

The following is a derivation of the coupled differential and linear equations which mathematically describe the calorimeter system. Equations to describe the wall temperature, bulk temperature, and thermocouple temperature are derived.

5.1 Wall Temperature:

Consider a small circular ring of length Δx, with a cross sectional area A, an inside perimeter P and a wall thickness t. Assume the ring is a material with a thermal conductivity $\underline{K}$. An average volume heat generation rate $\overline{Q}$, between x and $x + \Delta x$, is assumed to be depositing heat uniformly in the ring. The outside of the ring is adiabatic, but heat can enter or leave through either the left- or right-face by conduction. Heat may also leave the inside wall by convection to a stream with an average (between x and $x + \Delta x$) reference temperature $\overline{T}_B$. The heat transfer coefficient h is assumed constant over the length of the ring and is defined by,

$$h = \frac{\bar{Q}(A \cdot \Delta x)}{P \cdot \Delta x} \quad \frac{1}{(\bar{T} - \bar{T}_B)}$$

where $\bar{T}$ is the average ring temperature.

Since the temperature of the ring varies only in the x-direction, the differential equation describing the temperature will be one-dimensional and may be derived by means of a simple heat balance:

$$\boxed{\begin{array}{l}\text{Heat conducted in}\\ \text{through the left}\\ \text{face during time}\\ \Delta\theta\end{array}} + \boxed{\begin{array}{l}\text{Heat generated}\\ \text{in the ring}\\ \text{during time}\\ \Delta\theta\end{array}} = \boxed{\begin{array}{l}\text{Heat conducted out}\\ \text{through the right}\\ \text{face during time}\\ \Delta\theta\end{array}} + \boxed{\begin{array}{l}\text{Heat lost by}\\ \text{convection to}\\ \text{stream during}\\ \text{time } \Delta\theta\end{array}}$$

$$-KA \left.\frac{dT}{dx}\right|_x \Delta\theta + \bar{Q}(A \cdot \Delta x)\Delta\theta = -KA \left.\frac{dT}{dx}\right|_{x+\Delta x} \Delta\theta + h(P \cdot \Delta x)(\bar{T} - \bar{T}_B)\Delta\theta \qquad (1)$$

The derivative $(dT/dx)|_{x+\Delta x}$ can be expressed by the mean value theorem in terms of the derivative at x:

$$\left.\frac{dT}{dx}\right|_{x+\Delta x} = \left.\frac{dT}{dx}\right|_x + \left.\frac{d^2T}{dx^2}\right|_M \Delta x$$

where M is a point somewhere between x and $x+\Delta x$. Substituting this in equation (1) and rearranging we get,

$$KA \left.\frac{d^2T}{dx^2}\right|_M \Delta x - h(P \cdot \Delta x)(\bar{T} - \bar{T}_B) = -\bar{Q}(A \cdot \Delta x) \qquad (2)$$

Now dividing through by $(K \cdot A \cdot \Delta x)$ and letting the length Δx of the ring become vanishingly small forces the point M to approach the point x and $\bar{T}$, $\bar{T}_B$, and $\bar{Q}$ approach the value of the point x, giving

$$\frac{d^2T(x)}{dx^2} - \frac{hP}{KA}[T(x) - T_B(x)] = -\frac{Q(x)}{K} \qquad (3)$$

If the wall is of uniform density ρ_M, then $Q(x) = \rho_M \cdot \Gamma(K)$, where $\Gamma(x)$ is the mass heat generation rate at point x. The final equation for the wall is then,

$$\frac{d^2T_W(x)}{dx^2} - \frac{hP}{KA}[T_W(x) - T_B(x)] = -\frac{\rho_M}{K}\Gamma(x) \qquad (4)$$

5.2 Bulk Temperature:

As the fluid stream flows through the ring, it picks up heat from the wall through the convective process $(dq_W \cdot \Delta\theta)$ and has heat generated internally by the mass heat generation rate $(dq_\Gamma \Delta\theta)$. In a small section of length dx about x, the total incremental heat gained $(dq_T \cdot \Delta\theta)$ in time $\Delta\theta$ is given as,

$$dq_T \Delta\theta = dq_w \Delta\theta + dq_\Gamma \Delta\theta \tag{5}$$

Now dq_w is determined from the definition of the heat transfer coefficient,

$$dq_w = hdA(T_w - T_B) = h \cdot Pdx(T_w - T_B)$$

and

$$dq_\Gamma = \rho_H \cdot \Gamma(A_H \cdot dx)$$

where Γ is the mass heat generation rate, A_H is the flow area, and ρ_H is the density of water. Then equation (5) becomes,

$$dq_T \Delta\theta = [hPdx(T_w - T_B) + \rho_H \Gamma A_H dx]\Delta\theta \tag{6}$$

The heat which is added to the water causes a temperature rise, dT_B, which is defined by,

$$dq_T = w \cdot C_p \, dT_B \tag{7}$$

Combining equation (7) with equation (6) gives,

$$wC_p \, dT_B = hP \, dx(T_w - T_B) + \rho_H \Gamma A_H \, dx, \tag{8}$$

which can be rearranged to give the bulk temperature equation:

$$\frac{dT_B(x)}{dx} = \frac{hP}{w \cdot C_p} [T_w(x) - T_B(x)] + \frac{\rho_H A_H}{w \cdot C_p} \Gamma(x) \tag{9}$$

5.3 Thermocouple Temperature:

With the thermocouples located somewhere in the channel, the problem becomes one of relating the thermocouple temperatures to the bulk temperatures. A complete solution requires that the temperature and velocity profiles be known. Work done by Martinelli (ref. 3) under the simplifying assumptions of temperature-independent water properties, well-developed turbulent flow and the Nikuradse velocity profile has resulted in a predicted relation between the wall temperature, the centerline temperature, and the bulk temperature. The relation between these three variables is expressed as,

$$\alpha(Re, Pr) = \frac{T_w - T_B}{T_w - T_c} \tag{10}$$

where α is function of the Reynolds and Prandtl numbers.

An investigation of this relation over the range of Reynolds and Prandtl numbers for the typical calorimeter design presented in Section 10 shows that α is nearly constant (fig. 2). The parameter α is then taken as a measure of turbulence, since as $T_c \rightarrow T_B$, $\alpha \rightarrow 1$. For the calorimeter design presented, $\alpha \cong 0.91$, there is a predicted temperature difference of about 15° F between the bulk and the centerline temperature (fig. 3). This indicates the gross error which would be involved in assuming that the centerline temperature is the same as the bulk temperature.

If the thermocouple is positioned in the channel such that it is very nearly reading the bulk temperature then α will be approximately 1 and thus reduce this uncertainty. Assuming that the thermocouple is located somewhere between the wall and the centerline of the channel such that the thermocouple is reading approximately the bulk temperature, then equation (10) becomes,

$$\alpha(\mathrm{Re},\ \mathrm{Pr}) = \frac{T_w - T_B}{T_w - T_m} \tag{11}$$

where T_m is the assumed average water temperature and $T_m \cong T_B$. Now if α is nearly equal to 1 and is a constant then equation (11) suggests the linear relation,

$$T_m = \left(\frac{1}{\alpha}\right)T_B - \left(\frac{1 - \alpha}{\alpha}\right)T_w \tag{12}$$

Another source of error arises when the fluid temperature is measured. Disturbing influences of gamma heating and conduction in the thermocouple itself may cause the thermocouple to read a different temperature than the stream temperature at the junction. For example, gamma heating in the sensing tip will cause a temperature drop between the sensing tip and the stream. In addition with the thermocouple protruding from the wall, any heat conducted down the thermocouple from the wall to the sensing tip will tend to raise the indicated temperature even higher above the stream temperature. Both effects can be analyzed effectively by forming the general model given by,

$$T_T = a_1T_m + a_2T_w + a_3\Gamma \tag{13}$$

The coefficients of this relation are dependent on thermocouple construction and on the calculational model used to describe the thermocouple.

Eliminating T_m from equation (12) and equation (13) gives

$$T_T = C_1T_w + C_2T_B + C_3\Gamma \tag{14}$$

where

$$C_1 = \left[a_2 - a_1\left(\frac{1 - \alpha}{\alpha}\right)\right]$$

$$C_2 = a_1/\alpha$$

$$C_3 = a_3$$

Equation (14) expresses a linear relation between the thermocouple temperature T_T, which will be measured, and the wall and bulk temperatures and the gamma heating.

The coefficients a_1, a_2, and a_3 can be determined analytically once a physical model is set up for the thermocouples. The parameter α must be determined experimentally.

6.0 Mathematical Description of the System and its Solution

Equations (4), (9), and (14) constitute a system of coupled differential and linear equations:

$$\frac{d^2T_w(x)}{dx^2} - \frac{hP}{KA}\left[T_w(x) - T_B(x)\right] = -\frac{\rho_M}{K}\Gamma(x) \tag{4}$$

$$\frac{dT_B(x)}{dx} - \frac{hP}{wC_p}\left[T_w(x) - T_B(x)\right] = \frac{\rho_H A_H}{wC_p}\Gamma(x) \tag{9}$$

$$T_T(x) = C_1 T_w(x) + C_2 T_B(x) + C_3 \Gamma(x) \tag{14}$$

This system can be greatly simplified if the axial conduction of heat in the wall can be made negligible. Physically, this will happen if the conductivity, K, is low, the area A is small, or the heat transfer coefficient h is very large. In order to determine whether the axial conductivity in the wall could be neglected, a one-dimensional heat transfer calculation was performed using the proposed calorimeter design. The results of the calculation in indicated that about 99 percent of the heat generated in the wall was transferred radially to the stream. This proves that for this particular calorimeter design neglect of the axial conductivity introduces a very small error.

If equation (4) is multiplied by KA and assuming that $KA \rightarrow 0$, then the system becomes.

$$\left.\begin{aligned} 0 &= hP[T_w(x) - T_B(x)] - \rho_M A_M \Gamma(x) \\ \frac{dT_B(x)}{dx} &= \frac{hP}{wC_p}\left[T_w(x) - T_B(x)\right] + \frac{\rho_H A_H}{wC_p}\Gamma(x) \\ T_T(x) &= C_1 T_w(x) + C_2 T_B(x) + C_3 \Gamma(x) \end{aligned}\right\} \tag{15}$$

Eliminating T_W from equation (15) gives the following simplified system,

$$\left.\begin{aligned} \frac{dT_B(x)}{dx} &= \left[\frac{\rho_M A_M + \rho_H A_H}{wC_p}\right]\Gamma(x) \\ T_T(x) &= T_B(x) + \left[C_1 \frac{\rho_M A_M}{hP} + C_3\right]\Gamma(x) \end{aligned}\right\} \tag{16}$$

Integration gives the simplified integral equation,

$$T_T(x) = T_B(0) + \gamma \int_{x_0}^{x} \Gamma(\tau)d\tau + \beta \quad \Gamma(x) \tag{17}$$

where

$$\gamma = \left[\frac{\rho_M A_M + \rho_H A_H}{wC_p}\right], \ \beta = \left[C_1 \frac{\rho_M A_M}{hP} + C_3\right]$$

By differentiating equation (17), then integrating by parts, the final form of the solution for $\Gamma(x)$ is,

$$\Gamma(x) = \frac{T_T(x)}{\beta} + \frac{T_B(x_0)}{\beta} e^{-(\gamma/\beta)(x-x_0)} - \frac{\gamma}{\beta^2}\int_{x_0}^{x} e^{-(\gamma/\beta)(x-\tau)} \ T_T(\tau)d\tau \tag{18}$$

As can be noticed, the simplified system, equation (15), was reduced to an integral equation for $\Gamma(x)$, where the known temperatures were assumed to be those measured with the thermocouple protruding into the water stream. The system, equation (15), can also be solved for $\Gamma(x)$ in terms of the wall temperature, giving,

$$T_W(x) = T_B(x_0) + \gamma \int_{x_0}^{x} \Gamma(\tau)d\tau + \varphi\Gamma(x) \tag{19}$$

where

$$\varphi = [\rho_M A_M]/[hP]$$

This could be solved for $\Gamma(x)$ in the same manner as equation (18). If both wall and channel temperatures are measured, then equations (17) and (19) can be solved for $\Gamma(x)$ directly, giving:

$$\Gamma(x) = \frac{T_W(x) - T_T(x)}{[\varphi(1 - C_1) - C_3]} \tag{20}$$

The advantage of equation (20) is that it does not contain the parameter α. The only significant nonlinearity is the heat transfer coefficient. If both wall and water temperatures are monitored, then equation (20) provides a good means of obtaining $\Gamma(x)$. Equation (20) is also independent of the gamma heating in the water (ρ_H, A_H, $\Gamma(x)$).

Finally, thermocouples are to be placed at the inlet and at the outlet of the calorimeter flow tube. Flow mixing devices before these two thermocouples insure that the total ΔT is measured accurately. The integral of the gamma heating down the channel is then obtained as a check on the results from equations (18), (19), and (20).

7.0 Numerical Methods of Solving the Integral Equations

There are two methods of solution which may be used for these equations. The first utilizes the closed form solution for $\Gamma(x)$ (eq. (18)). This equation was derived under the assumption that the coefficients γ and β are constant, or can be considered constant with a small error resulting. The second method involves an iterative procedure and is a more direct approach, in that it operates directly on the integral equation (17).

Both methods require that a temperature profile be measured. The suggested method of preparing this temperature profile from the table of discrete measured values, which will be taken from the thermocouples, is to first smooth the experimental data points. This may be accomplished analytically. Then, using a plot of the smoothed data, solve for $\Gamma(x)$. This has the effect of removing random scatter in the thermocouple points before the errors can be propagated into the solution for $\Gamma(x)$.

7.1 Solution of $\Gamma(x)$ for γ and β Constant:

For equally spaced data points located a distance Δx apart and taken from a smoothed plot of the measured temperature profile, equation (18) gives,

$$\Gamma(x_{n+1}) = \frac{1}{\beta}\left[T_T(x_{n+1})\right] + \frac{1}{\beta}\left[T_B(x_0)e^{-(\gamma/\beta)x_{n+1}}\right] - \frac{\gamma}{\beta^2}\int_{x_0}^{x_{n+1}} e^{-(\gamma/\beta)(x_{n+1}-\tau)}\, T_T(\tau)d\tau \qquad (21)$$

The integral term can be written:

$$\frac{\gamma}{\beta^2}\int_{x_0}^{x_{n+1}} e^{-(\gamma/\beta)(x_{n+1}-\tau)}\, T\ (\tau)d\tau$$

$$= \frac{\gamma}{\beta^2}\, e^{-(\gamma/\beta)x_{n+1}} \int_{x_0}^{x_{n+1}} e^{(\gamma/\beta)\tau}\, T_T(\tau)d\tau$$

and by defining: $I_n \equiv \int_{x_0}^{x_n} e^{(\gamma/\beta)\tau}\, T_T(\tau)d\tau$, equation (21) becomes

$$\Gamma(x_{n+1}) = \frac{1}{\beta}\left[T_T(x_{n+1})\right] + \frac{1}{\beta}\left[T_B(x_0)\ e^{-(\gamma/\beta)x_{n+1}}\right] - \frac{\gamma}{\beta^2}\ e^{-(\gamma/\beta)x_{n+1}}\left[I_{n+1}\right] \qquad (22)$$

A recursion relation expressing I_{n+1} in terms of I_n can be found once a method of numerical integration is chosen. For the trapezoidal rule,

$$I_{n+1} = \int_{x_0}^{x_{n+1}} e^{(\gamma/\beta)\tau}\ T_T(\tau)d\tau = \int_{x_0}^{x_n} e^{(\gamma/\beta)\tau}\ T_T(\tau)d\tau + \int_{x_n}^{x_{n+1}} e^{(\gamma/\beta)\tau}\ T_T(\tau)d\tau$$

$$= I_n + \int_{x_n}^{x_{n+1}} e^{(\gamma/\beta)\tau}\ T_T(\tau)d\tau$$

and

$$I_{n+1} \cong I_n + (\Delta x/2)\ e^{(\gamma/\beta)x_n}\ T_T(x_n) + T_T(x_{n+1})\ e^{(\gamma/\beta)\Delta x} \qquad (23)$$

By using equation (23) and values of T_T from the smoothed curve con- construct a table of values of I_n. Then using equation (22), construct a complete profile of gamma heating values.

7.2 Solution of $\Gamma(x)$ for γ and β not Constant:

Equation (17) can be rearranged to give,

$$\Gamma(x) = \frac{T_T(x) - T_B(0)}{\beta} - \frac{\gamma}{\beta} \int_{x_0}^{x} \Gamma(\tau)d\tau \qquad (24)$$

where:

$$\gamma = \gamma(T,x), \quad \beta = \beta(T,x).$$

The method of solution is to choose an initial arbitrary function $\Gamma_0(x)$. With this function under the integral sign and after performing the integration, compute a revised function $\Gamma_1(x)$ using the known temperature distribution $T_T(x)$. Then insert $\Gamma_1(x)$ under the integral sign and calculate $\Gamma_2(x)$. The series of functions $\Gamma_n(x)$ generated in this way should converge toward the final stable value. The temperature dependence of γ and β can also be included in the iteration process. This method of solution results in a Neumann series of functions.

8.0 Number of Thermocouples Required and Interpolation Technique

The shape of the temperature profile to be measured is (to a first approximation) the same as the integrated gamma heating shape shown in figure 4. If this function is differentiated twice the shape shown in figure 5 results. It can be seen from figure 5 that this second derivative of the temperature profile can be approximated by straight line segments.

If the second derivative of a function is a straight line, this can then be expressed as

$$\frac{d^2T}{dx^2} = mx + b \tag{25}$$

Integrating equation (25) twice gives,

$$T = a_3x^3 + a_2x^2 + a_1x + a_0 \tag{26}$$

Thus, the temperature profile can be approximated in piece-wise segments by cubic equations. Each cubic equation reguires coefficients (a_3, a_2, a_1, a_0) to be specified completely. These four coefficients can be determined by making measurements at four distinct points and solving the resulting four simultaneous linear equations for (a_3, a_2, a_1, a_0).

It is assumed that any measurement of temperature will have some random error associated with it. The amount of error is not known in advance, but some means of reducing the effects of this error is desired. A method for doing this is to perform a least squares analysis on the data. This requires that the number of measurements exceed that number which is exactly required for a mathematical description of the system, that is, that the system be over-determined.

For the temperature profiles in this experiment, five measurements over any of the straight line segments discussed above will give a slightly over-determined system. Then at least five measurements must be made over the shortest line segment as shown in figure 5. This would be for the rods-in case with the line segment running between +4-in. and -2-in., or over a 6-in. length, which would indicate a maximum thermocouple spacing of 1.25 inches.

Since the straight-line segments in figure 5 shift as a function of bank height, the least squares method of fitting to preselected line segments is inadequate for practical application to this experiment. The argument for the amount of points required to perform a successful least squares fit (or to have a slightly over determined system) is still valid but a better method of eliminating the random error is required. If the least squares smoothing is performed over line segments, it is known as smoothing-in-the-small, while if performed over the entire curve it is known as smoothing-in-the-large. For smoothing-in-the-large, all the empirical data is expanded in a series of orthogonal functions, such as a Fourier Series. If a Fourier Series is used, special techniques are available to quarantee very rapid convergence of the series (coefficients decrease as n^{-3}). To remove the random data scatter, the series is truncated at the point where the series coefficients cease to follow the n^{-3} law and become randomly distributed in amplitude. When the random amplitude terms are rejected, so is most of the noise.

A requirement of the application of the Fourier Series technique of smoothing-in-the-large is that the data points be equally spaced. To have the data slightly over-determined it is necessary to have the thermocouples spaced no farther apart than 1.25 inches. Thus over the region of interest, from +16-in. to -18-in., referenced to the core horizontal midplane, it is necessary to have a minimum of 28 wall thermocouples and 28 thermocouples located in the channel stream.

The proposed method of data reduction is as follows:

(1) Perform a Fourier analysis on the thermocouple data points and truncate the series to remove most of the noise or experimental scatter.

(2) Use the truncated Fourier series to plot a smoothed curve for the temperature profile.

(3) Use the smoothed temperature profile to calculate the gamma heating distribution using equations (20), (22), or (24).

The main advantage of smoothing the data analytically rather than by eye is to get a quantitative measure of the noise in the system. This can be interpreted as a measure of system performance.

9.0 Experiment to Determine α and h

The proposed out-of-pile experiment would use an electrically heated flow tube having the same dimensions as the in-pile flow tube. The tube would be vertically oriented with water pumped through it at a known mass flow rate.

Electrically heating the flow tube will provide a constant heat flux given by,

$$(q/A)_o = (q/L)_o/P = (q_T/L)/P \qquad (27)$$

where P is the wetted perimeter, q_T is the total heat input along the heated length of the tube and L is the heated length.

This constant heat flux, with no axial conduction in the tube, will give a linear bulk temperature rise:

$$T_B(x) = T_B(x_o) + \left[\frac{T_b(x_f) - T_b(x_o)}{x_f - x_o}\right] x \tag{28}$$

where $(x_f - x_o) = L$ is the heated length.

To determine h, use the definition of the heat transfer coefficient

$$h(x) = \frac{(q/A)_o}{T_w(x) - T_B(x)} \tag{29}$$

Substituting equation (28) into (29) gives

$$h(x) = \frac{(q/A)_o}{\left[T_w(x) - \left\{T_b(x_o) + \left(\frac{T_b(x_f) - T_b(x_o)}{x_f - x_o}\right) x\right\}\right]} \tag{30}$$

The parameter α, assuming the coupling between the wall and the thermocouple is negligible, can be determined by noting

$$C_1 = (\alpha - 1)/\alpha$$

$$C_2 = 1/\alpha$$

$$C_3 = 0$$

This implies that $T_T = T_m$.

Then from the basic definition of α,

$$\alpha(x) = \frac{T_w(x) - \left[T_b(x_o) + \left(\frac{T_b(x_f) - T_b(x_o)}{x_f - x_o}\right) x\right]}{T_w(x) - T_T(x)} \tag{31}$$

The experiment requires that temperature profiles be taken down the wall and in the channel stream at a number of flow and heating rates. α and h would be correlated for each position (x).

10. Typical Calorimeter Design

The problem of recovering the gamma heating from the calorimeter can be solved only if the following design constraints are true. These are:

(a) Flow is turbulent which gives a reasonably large heat transfer coefficient and insures complete mixing of the bulk water.

(b) The tube wall is thin enough to make axial conduction negligible.

(c) The tube wall is large enough to have most of the heat ($\approx$90 percent) produced in the walls rather than in the coolant water.

(d) The tube should be small in diameter so that the local variation in gamma heating across the tube is small. However, the inside diameter of the tube cannot be too small since clad thermocouples must extend vertically from the wall into the stream. If the wetted length of the thermocouples is too short, the wall temperature will have a disturbing influence on the thermocouples.

(e) The thermocouples should be as small in diameter as possible to reduce the effect of direct gamma heating in them. They should be spaced close enough together to guarantee good data analysis in the presence of experimental error.

(f) The wall temperature must not exceed saturation temperature.

(g) Flow requirements must be capable of being met by the 30 psia ΔP which is available across the ring header.

(h) The secondary heating effects must be small.

The environment assumed to exist for this calorimeter design was the gamma heating in LA-7 at 60 MW, as shown in figure 6. A design which satisfies the above constraints is given below:

(a) The flow through the calorimeter is driven from the ring header. The flow is regulated from above the tank, where the mass flow rate and inlet bulk temperature are measured. Water flows through the vertical tube and exhausts into the core exit stream. The nominal mass flow rate is 438 lb/hr.

(b) The flow tube is constructed of stainless steel. The tube has an inside diameter of 0.375-inches and an outside diameter of 0.572-inches. Wall thickness is 0.0985-inches. At the mass flow rate of 438 lb/hr, the nominal velocity in the tube is 2.58-ft/sec. The Reynolds number varies from 15 800 at the assumed inlet temperature to 29 600 at the elevated outlet film temperature.

(c) The bulk inlet temperature is 135° F. The total bulk rise is approximately 70° F.

(d) The heat transfer coefficient varies down the channel from a value of 904 Btu/(hr)(ft^2)($^{\circ}$F) at the inlet to 1234 Btu/(hr)(ft^2)($^{\circ}$F) at the hot spot, based on the film temperature and the modified Colburn relation

$$(NU)_f = 0.023\ (Re)_f^{0.8}\ (Pr)_f^{0.33}$$

(e) The wall temperature is about 308° F at the hot spot, using the nominal mass flow rate of 438 lb/hr (saturation temperature is approximately 330° F at the outlet pressure). In practice, the flow will be manually adjusted to keep the measured wall temperatures below saturation.

(f) The secondary gamma effects will be approximately 10 percent of the primary gamma heating.

Figure 3 is a plot of the nominal wall, bulk, and centerline temperatures down the channel. Figure 7 shows some of the temperature dependent parameters as functions of the wall and bulk temperatures down the channel for this design.

The annular space between the flow tube and the containment can is evacuated to eliminate conduction and convection heat loss from the flow tube to the containment can. The temperatures of the clad thermocouples are entirely dependent upon radiant heat transfer. Calculations with $\epsilon = 0.10$ of the stainless steel clad give a temperature of 2020° F for the clad at the hot spot, which is excessively high. If the cladding were plated with platinum ($\epsilon = 0.97$), the resulting temperature would be 953° F, which is much more acceptable. Thus it is imperative that the clad thermocouple leads be plated with platinum or other material of high emissivity where they pass through the evacuated space.

11.0 Calorimeter Accuracy

The accuracy of the calorimeter results depends on the ability to measure the heat transfer coefficient h and the turbulence factor α in the out-of-pile experiment. It also depends on the measurement of the water and the wall temperatures during both the in-pile and the out-of-pile experiments. The largest error involved in determining $\Gamma(x)$ will be in the determination of h and α. It was determined that if equation (20) were utilized in determining $\Gamma(x)$, the accuracy of the gamma heating would depend mostly on how accurately h and α can be determined. For example, if a 10 percent error existed in both h and α, the total error in the gamma heating would be about 14 percent.

If the thermocouple is positioned in the channel stream such that it is very nearly reading the bulk temperature, then α will be approximately 1. This will reduce this uncertainty to a few percent. The errors involved in determining the heat transfer coefficient will be the electrical heat input, the mass flow rate, the tube dimensions, the thermocouple readings, and and the physical properties of water. It also depends on how closely the out-of-pile data fit whatever correlations are used. For the out-of-pile test the electrical heat input can be determined to within 5 percent by induction heating. For the 3/8-in. ID tube the mass flow rate can be measured to within 2 to 3 percent. The thermocouples can be calibrated to within a few tenths of a degree. It seems reasonable to expect an uncertainty of less than 10 percent in h.

The uncertainty finally quoted after in-pile measurements are done will depend a lot on how well the 3 sets of data (from film drop, bulk rise, and integral bulk) agree. But an uncertainty of 10 to 15 percent (95 percent confidence) is expected, while considerably better accuracy is possible if all the data, in- and out-of-pile, agree.

12.0 References

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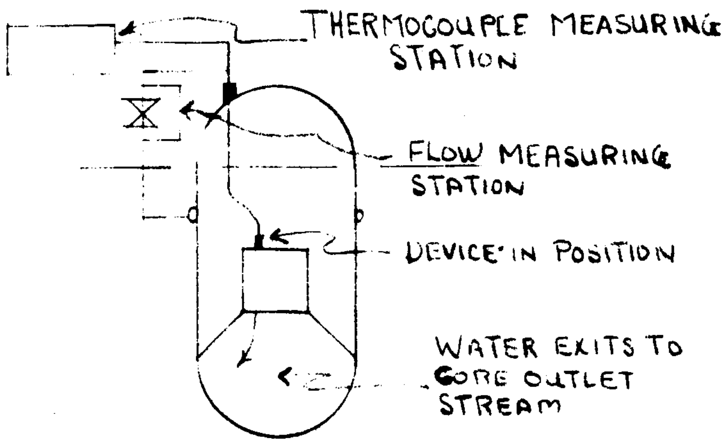
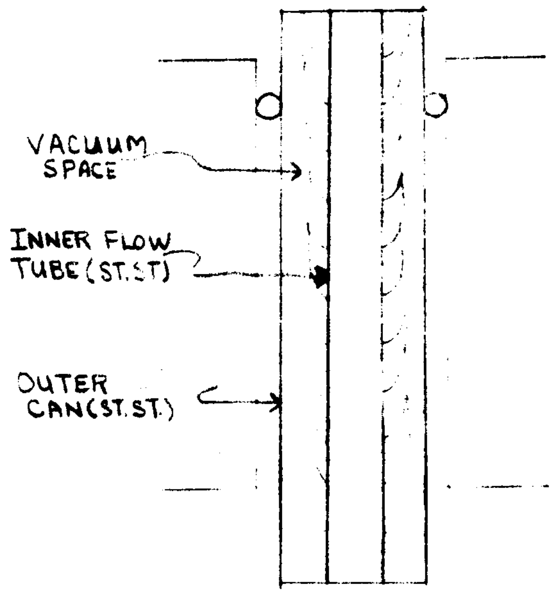
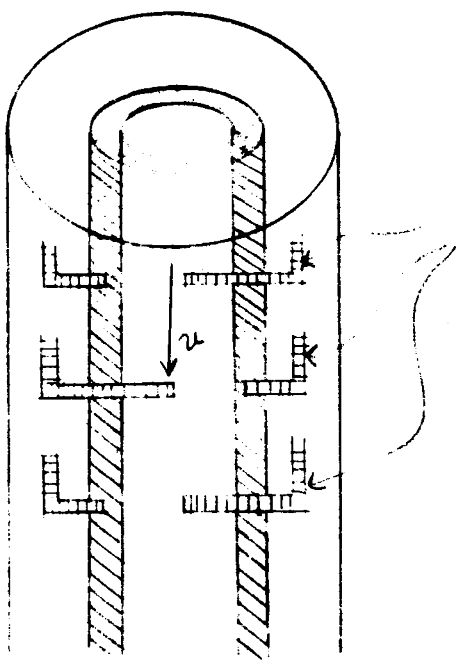
FIGURE - 1

~~CONCEPT~~ SKETCH OF CALORIMETER







K+E SEMI-LOGARITHMIC 359-71
KEUFFEL & ESSER CO. MADE IN U.S.A.
3 CYCLES X 70 DIVISIONS

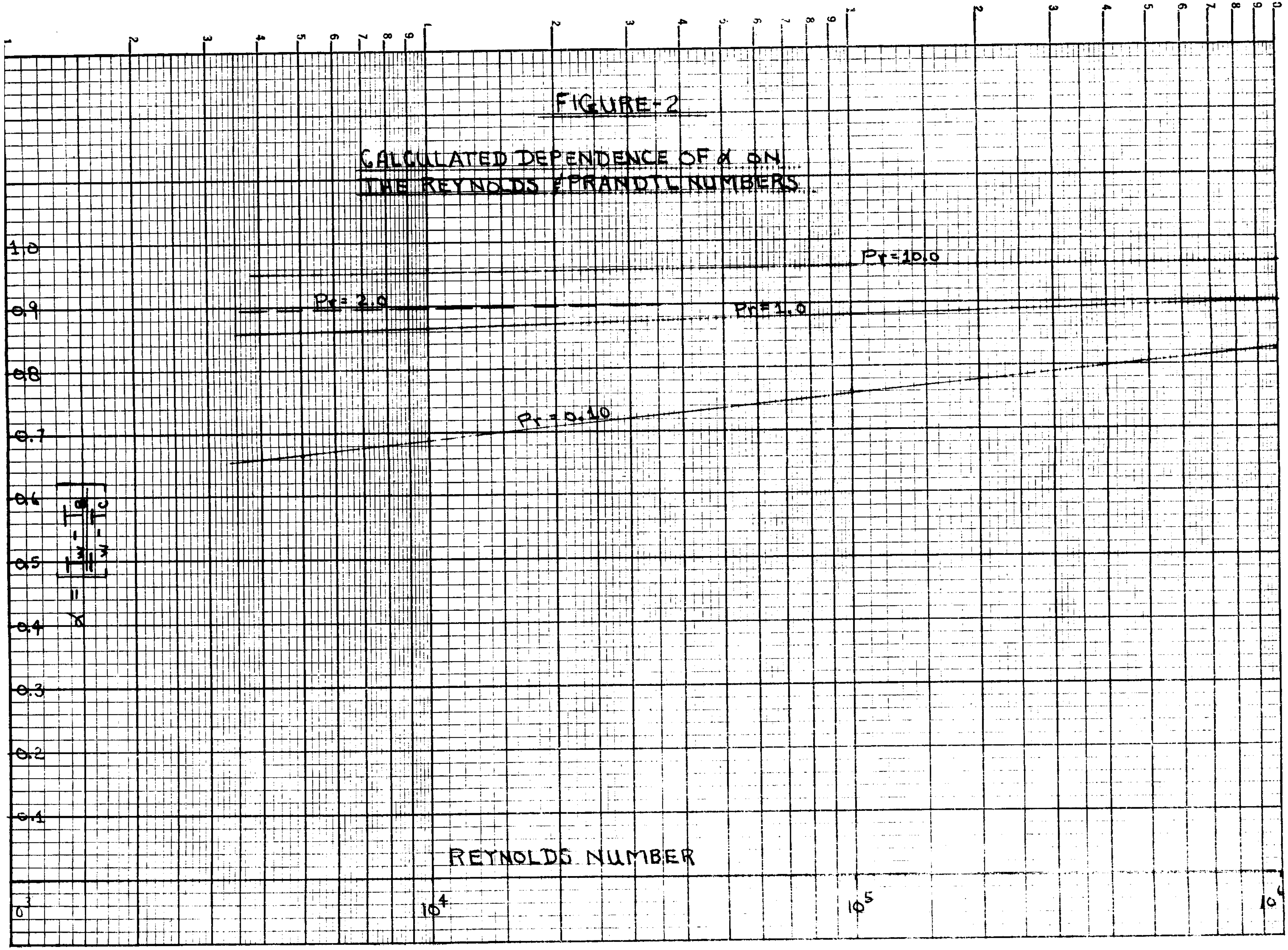
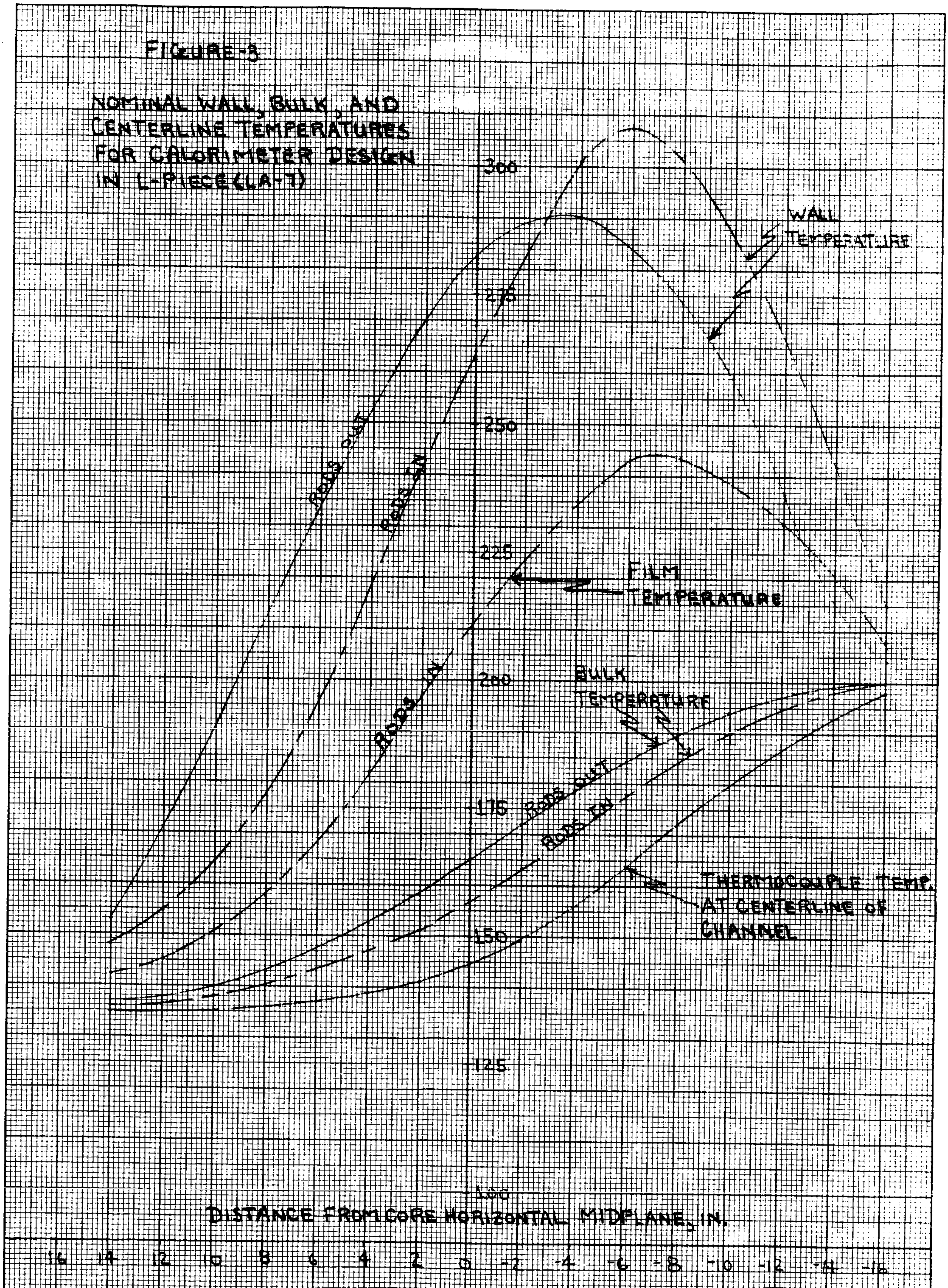


FIGURE-2

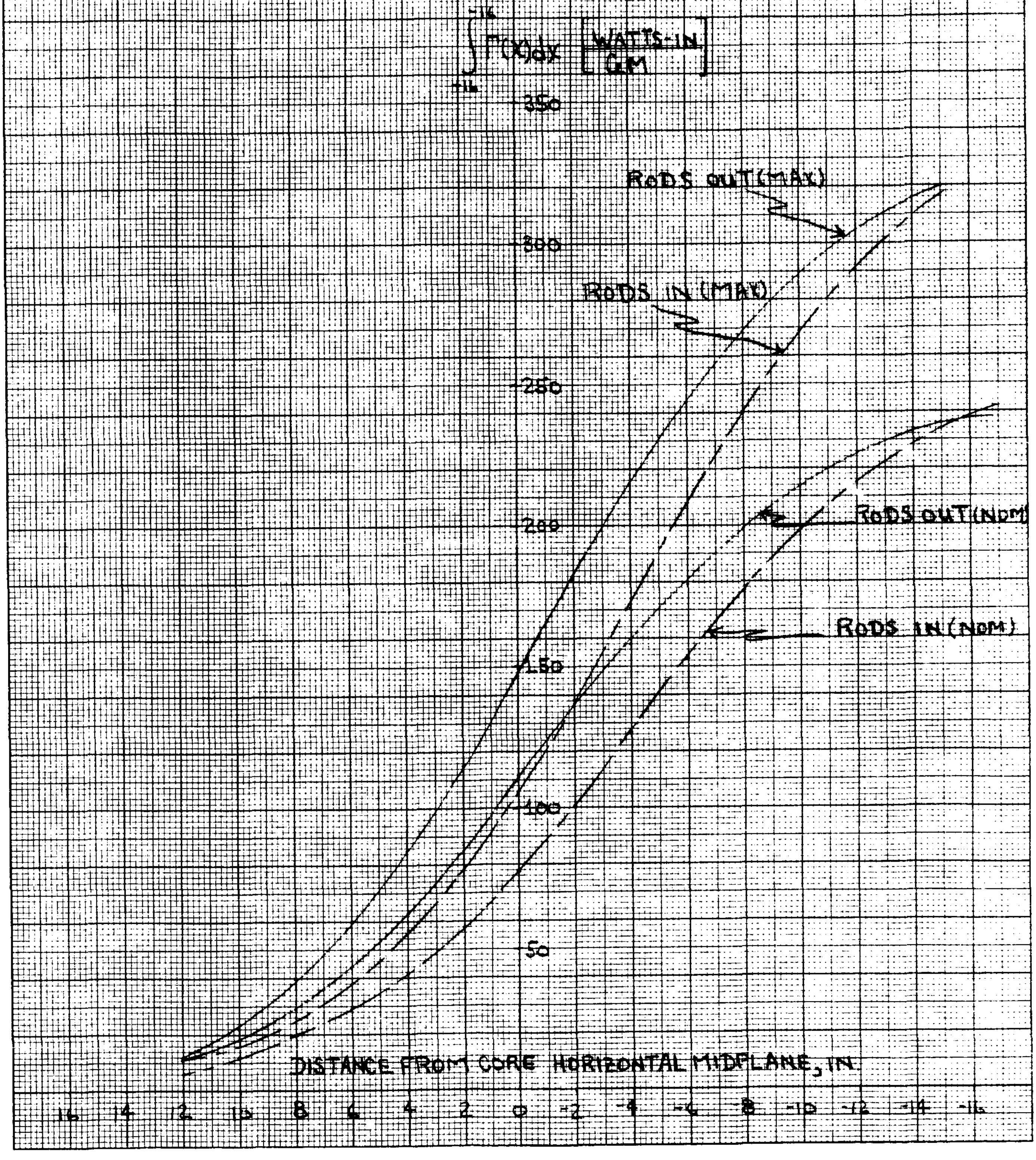
CALCULATED DEPENDENCE OF α ON THE REYNOLDS & PRANDTL NUMBERS



KEUFFEL & ESSER CO. 18 X 25 CM. MADE IN U.S.A.

FIGURE - 4

INTEGRATED GAMMA HEATING IN L-PIECE (LA-7)



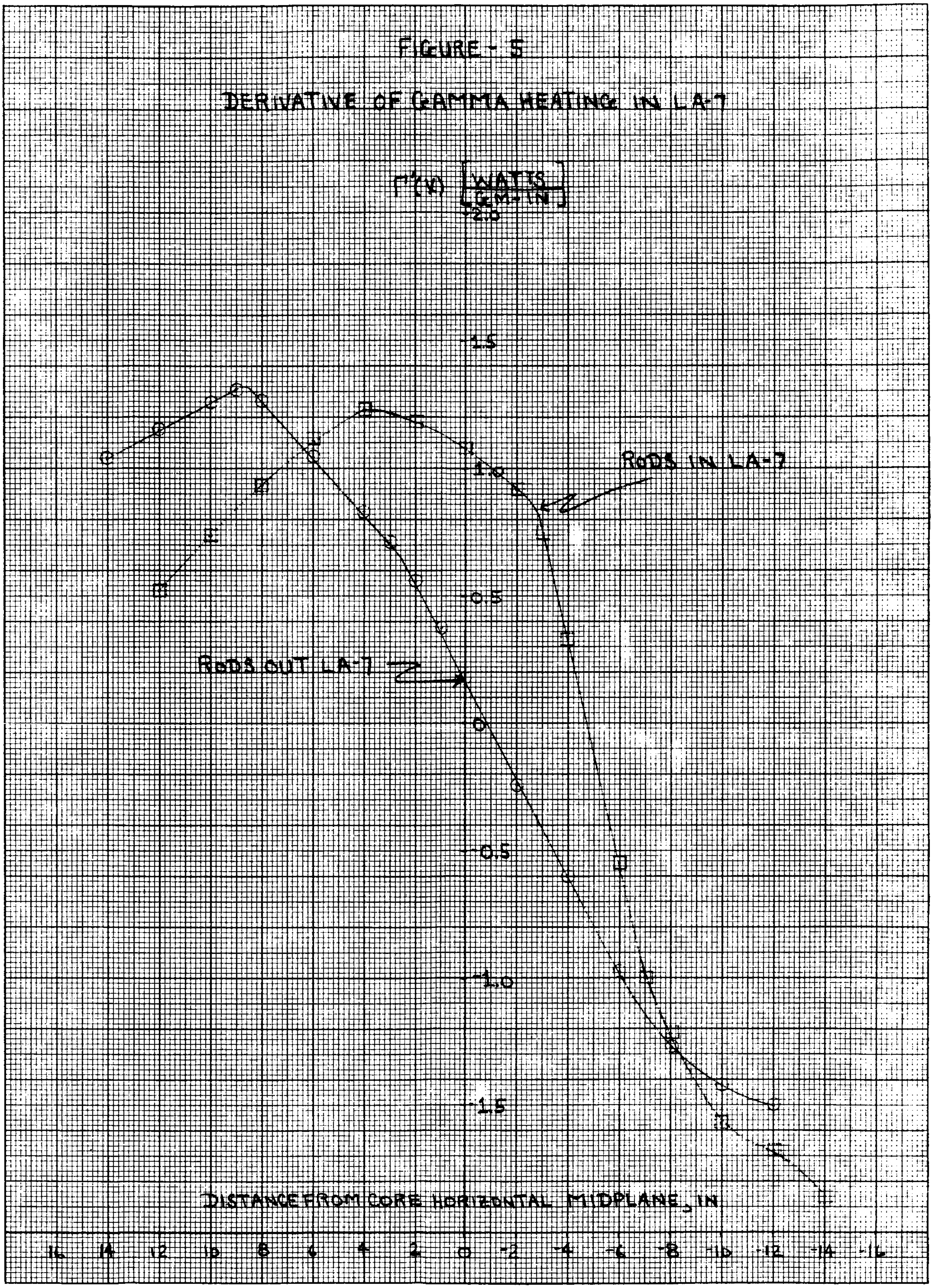


FIGURE - 5

DERIVATIVE OF GAMMA HEATING IN LA-7

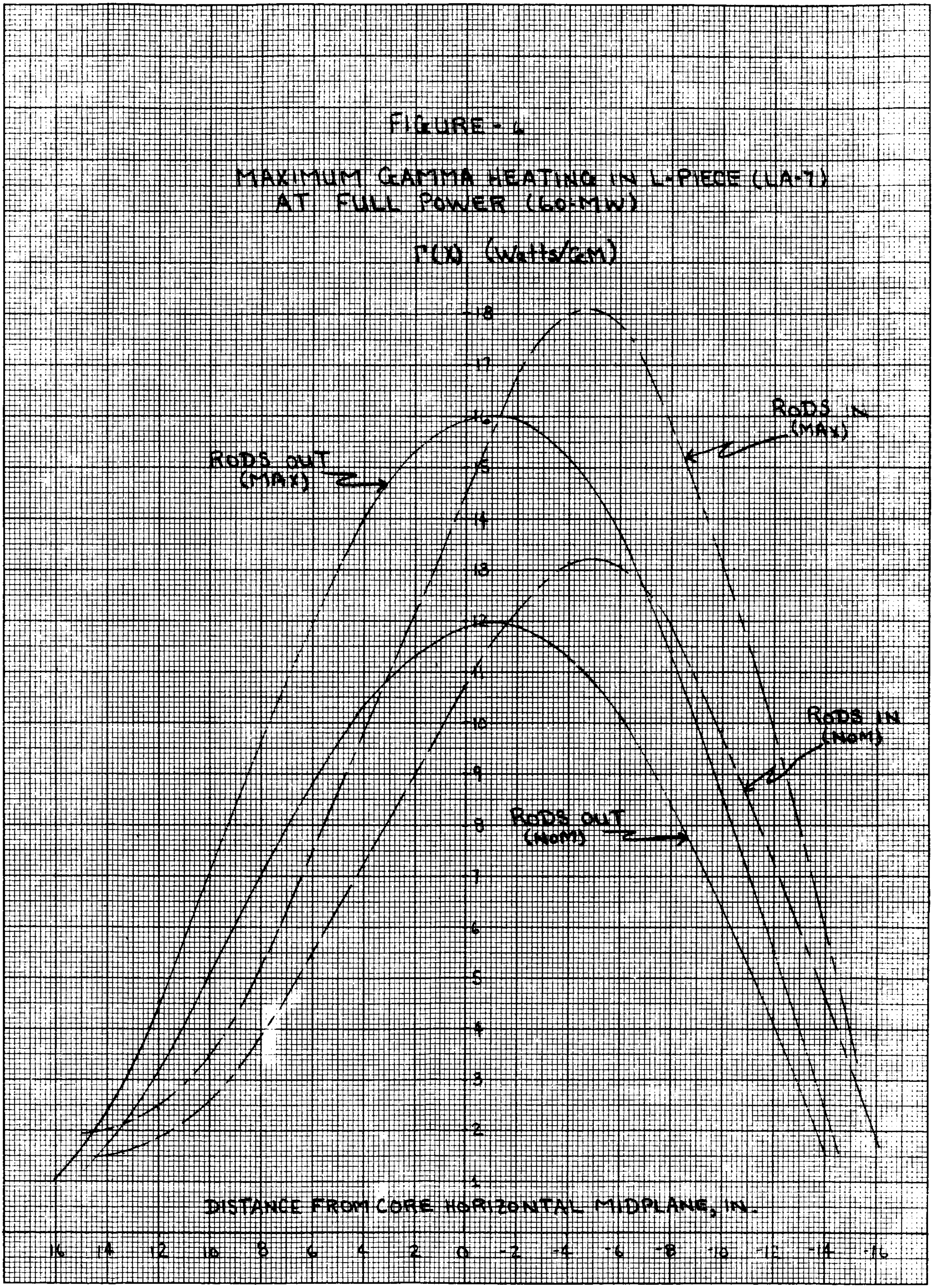


FIGURE - 6
MAXIMUM GAMMA HEATING IN L-PIECE (LA-7)
AT FULL POWER (60-MW)
Γ(X) (Watts/CM)
RODS OUT (MAX)
RODS IN (MAX)
RODS IN (NOM)
RODS OUT (NOM)
DISTANCE FROM CORE HORIZONTAL MIDPLANE, IN.
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16

FIGURE - 7

FILM TEMPERATURE AND ASSOCIATED PARAMETERS FOR CALORIMETER DESIGN